Recommended Best Management Practices to Minimize the Likelihood of Sediment Delivery to Streams by Logging Induced Landslides in Eastern Kentucky

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SCOPE AND PURPOSE

This document was prepared at the request of the Appalachian Citizens' Law Center, Kentucky Heartwood, and the National Wildlife Federation. Its purpose is fourfold:

- To summarize the occurrence of landslides and current state of publicly available landslide information in Kentucky.
- To summarize the large body of existing scientific literature on the relationship between logging and landslides.
- To summarize selected state logging best management practices (BMPs) dealing with the assessment and avoidance of sedimentation problems related to logging-induced landslides.
- To propose a set of best management practices (BMPs) intended to reduce the likelihood of logging-induced landslides, consistent with the geologic setting and data availability in Kentucky, and with consideration of potential adaption in other Appalachian states.

Throughout this document, "landslide" is used it its broadest sense to include downslope movement of earth materials by sliding or flowing under the influence of gravity at a rate greater than soil creep, including rockslides, mudslides, mudflows, debris flows, earthflows, slumps, slips, and similar phenomena.

LANDSLIDES IN EASTERN KENTUCKY

The Appalachian Mountains, including eastern Kentucky, have long been recognized as one of the most landslide-prone regions of the United States (Radbruch-Hall et al., 1982; Mirus et al., 2020). Systematic efforts to characterize Appalachian landslide occurrence and susceptibility date back to a U.S. Geological Survey program of mapping existing features and qualitatively evaluating landslide and debris flow hazard susceptibility for hundreds of 7.5-minute topographic quadrangles during the 1970s and 1980s, which resulted in the production of hundreds of hand-drawn open-file maps and more formal publications. Since then, landslide occurrence and susceptibility mapping in Appalachia has been largely left to state geological surveys or governments.

In Kentucky, the Kentucky Geological Survey (KGS) has assembled a statewide landslide database that includes a regularly updated list of known historical landslide locations and any other available information, landslides shown on existing 1:24,000 scale geologic maps in Kentucky, landslides identified from interpretation of airborne lidar coverage, landslides identified from aerial photographs by U.S. Geological Survey scientists, and areas susceptible to debris flow as inferred by U.S. Geological Survey scientists (Crawford, 2014).

KGS has also started to produce a series of FEMA-funded landslide susceptibility maps for individual counties using machine learning methods applied to lidar-based landslide inventory maps. At present, susceptibility maps are available for the five counties comprising the Big Sandy Area Development District (Pike, Martin, Magoffin, Johnson, and Floyd). Maps for the counties comprising the Kentucky River Area Development District (Breathitt, Knott, Lee, Leslie, Letcher, Owsley, Perry, and Wolfe) are in preparation. The KGS landslide database layers and susceptibility maps are available as an interactive online map at:

https://kgs.uky.edu/kygeode/geomap/?layoutid=25.

Each of the susceptibility maps is also available as a PDF document with explanatory text (Crawford et al., 2022 a,b,c,d,e) that can be freely downloaded from the KGS website.

The Kentucky susceptibility map creation workflow has been described in the peer-reviewed scientific literature (Crawford et al., 2021; also see Crawford et al., 2022 f). It uses a logistic regression model including eight topographic variables associated with landslides identified on high-resolution lidar topographic maps and their derivatives (e.g., lidar-derived hillshade images). Woodard et al. (2023) include Kentucky Geological Survey results from Magoffin County in an assessment of difficulties in developing modern landslide susceptibility maps over large regions for which limited data are available.

In addition to the topographic variables used to generate the susceptibility maps, KGS research has shown that weak strata such as shale, coal, and underclay layers can localize landslides (Crawford, 2014; Chapella et al., 2019).

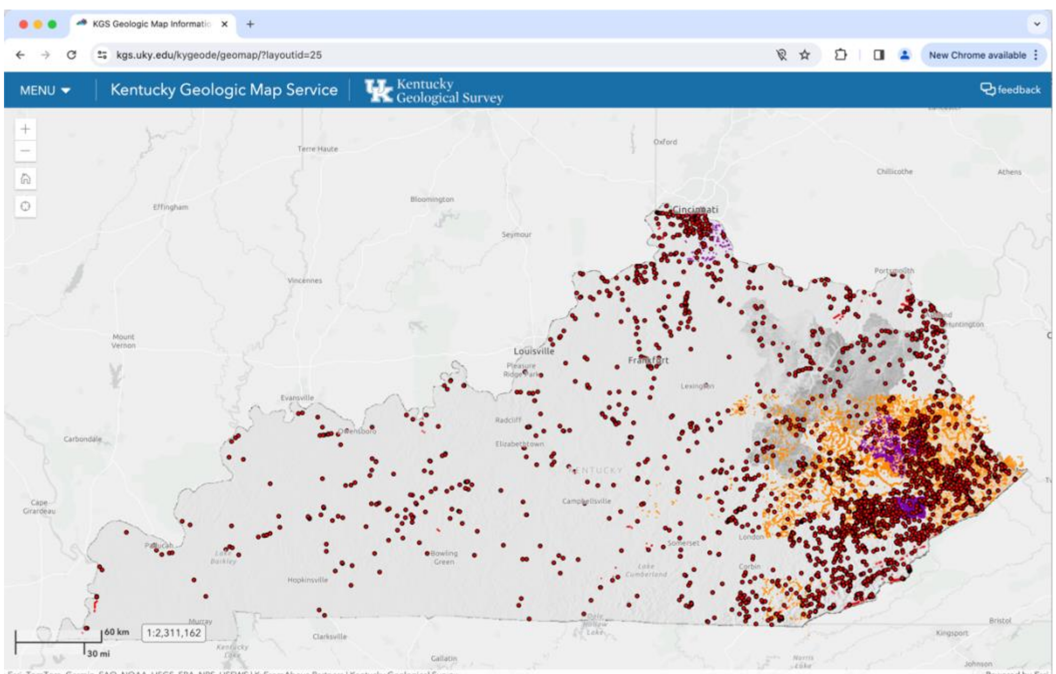

Figure 1—Screen capture from the Kentucky Geological Survey map service displaying landslide location information.

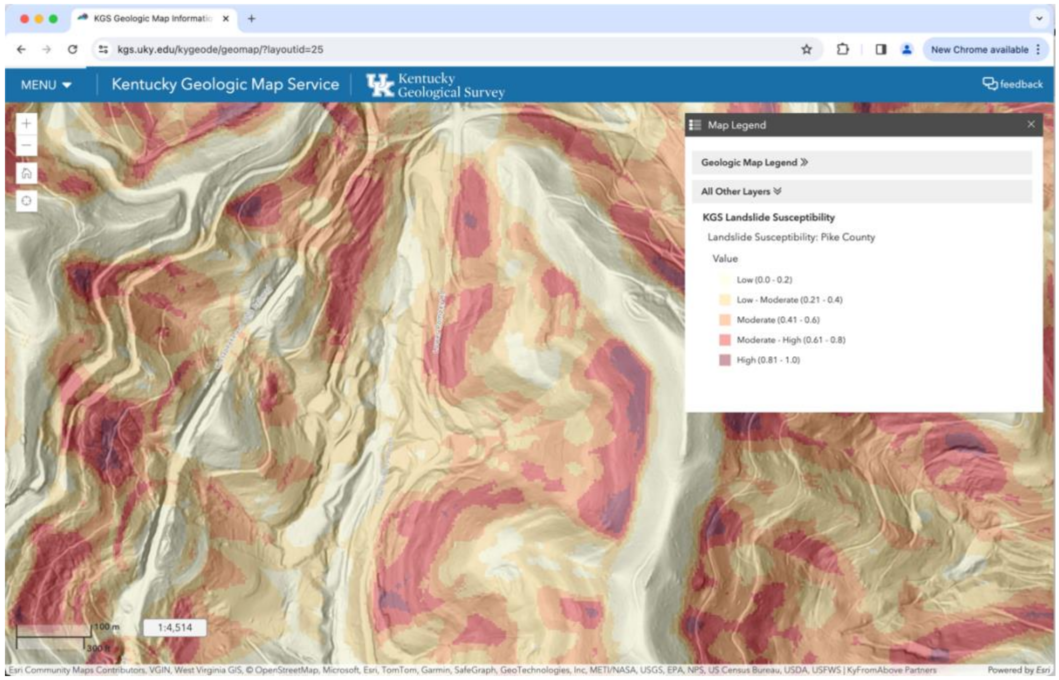

Figure 2—Screen capture showing a portion of the Kentucky Geological Survey landslide susceptibility map for Pike County draped over a 5-ft lidar multidirectional hillshade image of the area.

Neighboring states have also undertaken landslide susceptibility assessment and map production. Of particular note, Lessing et al. (1976) and Lessing et al. (1994) produced a series of landslide susceptibility maps for West Virginia. Those legacy maps, along with previous U.S. Geological Survey maps, were key components in the development of modern lidar-based landslide inventory, susceptibility, and risk maps available through the West Virginia GIS Technical Center (https://wvgis.wvu.edu). Like the Kentucky susceptibility maps, the West Virginia susceptibility maps leverage machine learning methods to determine susceptibility based upon the characteristics of landslides inventoried using airborne lidar coverage. Development of the model is described in a document available from the West Virginia GIS Technical Center (WV GIS TC, 2022). The North Carolina Geological Survey has also developed an interactive landslide website (https://experience.arcgis.com/experience/b55c8497d115400aa09d9cb7a27f5dc8/page/page_7/) with the ability to display known landslide points and polygons, landside deposits, and landslide susceptibility maps for some counties in western North Carolina.

LOGGING AND LANDSLIDES IN STEEP FORESTED WATERSHEDS

The effects of logging on the landscape are well established in the scientific literature. Charles Lyell wrote about the evidence of post-logging erosion, valley incision, and ground cracking he observed in Georgia and Alabama during 1846 in an 1853 revision of his three-volume *Principles of Geology*, which is widely recognized as a foundational document of modern geology (Wool, 2001). Although he did not refer specifically to landslides in his 1846 account of logging consequences, Lyell (1853) refers repeatedly to the importance of landslips, as he described them, in the enlargement of ravines and valleys such as those he described as consequences of logging. Nearly a century later, Hirata (1939) wrote, “Landslides, many of which are caused by heavy rains or earthquakes, land creep, and surface erosion, are specially frequent in deforested areas." He also observed that Japanese cedar plantations and bamboo forests offered less protection against landsides than broadleaved deciduous virgin forests. Swanston (1974) provided an early assessment of landslides related to logging in the western United States, including citations to work going back as far as 1950. DeGraff (1979) demonstrated that vegetative type conversion (which he defined as conversion of tree and brush cover to grassland cover) increased visible landslide activity by 300 percent in a Utah watershed and wrote "Vegetative-type conversion apparently has a landslide-inducing potential similar to that of clear-cutting and road building."

In a comprehensive modern review of landslides and their relationship to land use, Sidle and Ochiai (2006) describe in detail the relationship between trees and landslides on forested slopes. They state that the effect of trees on slope stability is a combination of 1) root strength that is generally considered a component of the cohesive strength of soil and 2) a reduction of soil wetness through a combination of canopy interception and evapotranspiration. Of the two, they consider root strength to be the more significant agent of stability. Sidle and Ochiai (2006) go on to summarize numerous studies demonstrating the role of logging on landslide generation in forested watershed, including the gradual loss of root strength in the years after logging. Sidle (1992) developed a mathematical model to evaluate the effects of logging on slope stability, concluding that alternating thinning and clear-cutting and clear-cutting along reduce slope stability more than shelterwood and partial logging.

There do not appear to be any published studies specifically investigating the relationship between logging and landslides in Appalachia, including eastern Kentucky, although Wooten et al. (2016) write with reference to their work in North Carolina, "Forest cover is an important stabilizing factor on hillslopes by intercepting precipitation, increasing evapotranspiration, and reinforcing roots" and "Anthropogenic influences have increased the frequency of mass wasting for a given storm event above natural historical levels through changes in vegetation and disturbances on mountain slopes".

The published scientific literature on the relationship between logging and landslides around the world is too extensive to review completely in this report. Google Scholar searches using the keywords "logging" and "landslides" and, separately, "logging" and "slope instability" yield about 59,500 and 45,400 results, respectively. The paragraphs below summarize a small selection of the relevant literature to demonstrate the near universality of logging as a potential cause of landslide problems.

In a study of the effects of clear-cutting and road construction on landslides in the Cascade Range of Oregon, Swanson and Dyrness (1975) concluded that landslide activity along logging roads and clear-cut areas increased by a factor of about 5 over a 20-year period. Reid and Keppeler (2012) analyzed landslide activity after second-entry partial clearcut logging in northern California and found that large landslides occurred at rates 10 times higher in logged areas and 100 times higher along roads, and that the volume rate of landslide activity associated with roads in logged areas was more than 3 times that from roads in not-logged forested areas. They also found that the largest slides occurred 9 to 14 years after logging and within "a few years" of pre-commercial thinning. Montgomery et al. (2000) analyzed 3224 post-logging landslides on commercial timberlands in Oregon and Washington, concluding that landsliding in their study area occurred at 3 to 9 times the regional background rate. They also concluded that landslides in their logged study area could be triggered by 24-hour rainfall events with recurrence intervals as small as 4 years.

Based on an analysis of 1004 landslides in British Columbia, Jakob (2000) concluded that the frequency of landslides in logged areas was 9 times higher than that in undisturbed forests and that logging-related landslides occurred on gentler slopes than natural landslides (in part because exceptionally steep slopes were not logged). He reported that most of the landslides resulted from road fill failures and within harvest areas. In a study evaluating 61 years of data from British Colubmia, Wolter et al. (2010) likewise found that logging related landslides required lower slopes to initiate than natural landslides and that, overall, the logging-related landslide rate was 9 times the natural rate. Guthrie (2002) found that the number of landslides following logging increased by factors of 3 to 16 in three different watersheds and 2 to 12 times more landslides reached streams after logging than before logging.

Imaizumi et al. (2007) studied an area in central Japan that had been subjected to rotational forest management since 1912 and found that the direct effect of clearcutting on landslide activity was in stands clearcut 1 to 10 years earlier with effects continuing up to 25 years after logging, an increase of 4 times the amount observed in control areas, which they attributed to a decay of root strength after logging. They also found that landslides continued to supply sediment for 45 years after logging in one watershed. Sato et al. (2023) studied landslides on plantation forests in Japan and concluded that the return period of landslides in their mature forest study area (> 40 years old) was 3 times higher than that for landslides in their immature forest study area (10 to 30 years old).

Steinacher et al. (2009) performed a numerical study in which they quantified the contributions of both tree roots and tree strength to slope stability for seven different hypothetical slopes. They showed that even for small amounts of root cohesion, deforestation decreases slope stability in the long term as roots decay. Hruška et al. (2023) conducted geophysical investigations at two locations in Moravia and the Czech Republic, concluding that logging led to incipient soil/rock movement and significant increases in wetness that they attributed to post-logging development of new rainfall infiltration pathways.

An important thread running through all of the cited landslide studies is that they demonstrate increased landslide activity was associated with specifically with logging and not simply a homogeneous regional response to factors such as rainfall; otherwise, there would have been little difference in landslide occurrence between logged and not-logged areas subjected to essentially the same amount of rainfall.

STATE LOGGING BMP AND FOREST PRACTICE DOCUMENTS

This section summarizes a subset of existing state BMP and forest practice documents with specific reference to landslides for two groups of states: The first group comprises Kentucky and neighboring states, reflecting current practices in central Appalachia and the eastern midcontinent. The second group comprises states that have adopted more rigorous and stringent practices up to and including promulgation of detailed forest practice rules specifically addressing the geologic evaluation of potentially unstable slopes.

Kelly and Crandall (2022) published an overview of the variety of state forestry practice policies across the United States and wrote, "Some states have codified BMPs into regulations, frequently by incorporating them into Forest Practices Acts; other states have maintained entirely voluntary BMPs and have focused on landowner and logger education to ensure BMPs are adopted." Although dated, Laird (2001) provides a useful summary of the integration of geologic assessments with timber harvest plans in the Pacific Northwest shortly after the adoption of existing forest practice rules.

Table 1 lists the states for which existing BMP, forest practices rules documents, and forest practices acts were reviewed; provides URLs for the documents reviewed; indicates whether the documents specifically reference landslides in relation to logging activities; and indicates in its fourth column whether detailed prescriptive BMPs related to landslide prevention are codified in the forest practice acts or regulations, as opposed to generic requirements or recommendations to avoid situations that could deliver sediment to streams.

Logging on federal land is generally exempt from state mandated BMPs; however, federal land managers may choose to follow BMPs developed for the states in which the managed lands are located.

Table 1. Logging best management practice and forest practice documents reviewed for this report. To avoid duplication and because of their wide variety of formats and authorship, the documents linked below are not included in the reference list at the end of this report.

State	Forest Practice or BMP Document URL	Mentions Landslides	Codified Landslide BMPs
Kentucky	https://eec.ky.gov/Natural-Resources/Forestry/ky-master-logger-program/Documents/Forest%20Conservation%20Act%20Statutes.pdf https://eec.ky.gov/Natural-Resources/Conservation/Agriculture%20Water%20Quality%20Act%20Documents/Ky%20Ag%20Water%20Quality%20Plan%20December%202020.pdf https://eec.ky.gov/Natural-Resources/Forestry/Kentucky%20Forest%20Conservation%20Act%20Information/Kentucky%20Logging%20BMP%20Field%20Guide%20FOR%20130.pdf	No	No
Virginia	https://dof.virginia.gov/wp-content/uploads/VAs-Forestry-BMP-Field-Guide_pub.pdf	No	No
West Virginia	https://code.wvlegislature.gov/pdf/19-1B-1/ https://wvforestry.com/pdf/DOFbmpManual2018.pdf	No	No

Tennessee	https://www.tn.gov/content/dam/tn/agriculture/documents/forestry/2023/Forestry-BMP-Guide.pdf	Yes	No
Ohio	https://dam.assets.ohio.gov/image/upload/ohiodnr.gov/documents/forestry/factsheets/BMPsErosionControlLogging.pdf	No	No
Indiana	https://www.in.gov/dnr/forestry/files/BMP.pdf	No	No
Missouri	https://mdc.mo.gov/sites/default/files/2020-09/woody_biomass_bmp_book.pdf	No	No
Pennsylvania	https://extension.psu.edu/best-management-practices-for-pennsylvania-forests	No	No
North Carolina	https://www.ncforestservice.gov/publications/BMP2021/2021NCFSBMPManual.pdf	No	No
Colorado	https://csfs.colostate.edu/wp-content/uploads/2020/08/2018_BMP_Audit.pdf	No	No
Wyoming	https://wsfd.wyo.gov/forest-management/bmp-s	Yes	No
Montana	https://dnrc.mt.gov/_docs/forestry/FinalBMP_VersionForWeb10_1_15.pdf	Yes	No
New Mexico	https://www.emnrd.nm.gov/sfd/wp-content/uploads/sites/4/19-20-4_NMAC_eff09142007.pdf https://www.emnrd.nm.gov/wp-content/uploads/sites/4/ForestPracticesGuidelines2008.pdf	Yes	No
Washington	https://www.dnr.wa.gov/about/boards-and-councils/forest-practices-board/rules-and-guidelines/forest-practices-board-manual	Yes	No
Oregon	https://knowyourforest.org/learning-library/forest-protection-laws https://www.oregon.gov/odf/documents/workingforests/fp-technical-guidance-identifying-slope-retention-areas.pdf	Yes	Yes
California	https://bof.fire.ca.gov/media/qs5p1yk4/2024-forest-practice-rules-and-act-final.pdf https://www.conservation.ca.gov/cgs/Documents/Publications/CGS-Notes/CGS-Note-45.pdf https://www.conservation.ca.gov/cgs/Documents/Publications/CGS-Notes/CGS-Note-50.pdf	Yes	Yes
U.S. Forest Service	https://geodata.geology.utah.gov/pages/view.php?search=&k=&modal=&display=list&order_by=field87&offset=9150&per_page=48&archive=0&sort=DESC&restypes=&recentdaylimit=&foredit=&ref=2550	Yes	Yes

All of the logging BMP or forest practice rule documents reviewed addressed steep slopes in the context of stream management zones, erosion, and runoff management. Only 7 out of 15, however, specifically mention landslides.

Some of the documents include language that can be broadly interpreted to include landforms or conditions characteristic of landslides or landslide-prone slopes. The Indiana BMP document, for example, includes the statement “Use soil, topographic, and aerial maps to locate poorly drained, high erosive, or wet areas to avoid” among its planning practices and “Minimize steep slopes and poorly drained areas as log-landing locations” among its items of caution. Poorly drained and wet areas on slopes can be indications of active or potentially active landslides, but the Indiana document does not specifically mention landslides or offer any additional detail. The Missouri document states, “Soil needs to be managed based on site-specific characteristics” but does not specifically state that the site-specific characteristics might include landslide susceptibility.

The Kentucky Forest Conservation Act (KRS 149.330 through 149.355) states, “No logger or operator shall conduct any timber harvesting operations in a manner that is causing or will likely cause water pollution.” The Kentucky Agriculture Water Act (KRS 224.71-100 through 224.71-140) further mandated development of a statewide agricultural water quality plan. As developed, the plan has silvicultural provisions including the minimum requirement that “Practices shall be implemented to control erosion that can deliver sediment to streams or channels from disturbed ground other than roads, trails, and landings.” Table 1 includes hyperlinks to the Kentucky Forest Conservation Act, Kentucky Agriculture Water Quality Plan, and the Kentucky Logging BMP Field Guide.

Although the Kentucky Forest Conservation Act, Agricultural Water Quality Act, and Logging BMP Field Guide do not specifically mention landslides, delivery of soil and rock to a stream by way of a landslide or debris flow developed from a landslide is a form of sediment delivery that constitutes water pollution. The Kentucky Logging BMP Field Guide refers to “steep slopes that may or may not be too steep to log” in the description of a harvest planning map and “steep areas were verified as being too steep to skid or safely fell timber” in the description of a harvest planning walkthrough; however, it does not provide additional details or guidance about the definition or consequences of “too steep”. Like other BMP documents, the Kentucky document addresses stream management zones (SMZs) with requirements that 50 percent of the overstory be retained near perennial streams and 75 percent near cold water aquatic habitats. The width of stream buffers within which overstory must be retained range from 25 feet (slopes < 15%) to 50 feet (slopes > 16%) for perennial streams and 100 feet regardless of slope for cold water aquatic habitats. The Kentucky BMP document also specifies setbacks of 50 feet to 100 feet for roads, trails, and landings, depending on the slope and stream type. The document also provides BMPs for “sinkholes with openings and other naturally occurring openings in the ground” aimed at preventing runoff, soil, and logging debris from entering sinkholes and giving rise to water quality problems. Although the Kentucky BMP document does not specifically include landslides, it does (1) state that some slopes may be too steep to log, (2) recognize the importance of retaining trees in some classes of sensitive areas, and (3) emphasize that sinkholes—which are, like landslides, geologic features—need to be considered when planning logging operations.

The Tennessee logging BMPs list landslides as a type of sensitive area, which the document defines as "site-specific natural or topographic features of consequence to aquatic resources…". The Tennessee BMP document states that skidding and road location should be avoided within sensitive areas, runoff should not be directed into sensitive areas, and soil exposure and compaction and should be limited in sensitive areas. The document does not include any guidance specifically regarding identification or assessment of landslides or landslide prone slopes.

The Virginia document states, "Tall cut slopes may require back-sloping to achieve stability and successful revegetation. Slopes of 1:1 or flatter are preferred if the terrain permits." It does not address landslides that may exist or develop in areas that are not cutslopes.

The Wyoming document includes a photograph of a landslide in a section titled "Naturally Caused Sediment" and a statement that "Sediment originates from mudslides…"

The Montana document mentions landslides three times in the context of forest ecosystem disturbance and sediment sources, and states "…events such as landslides and floods have had considerable influence on forest and watershed function." The document does not include any guidance regarding identification or assessment of landslides or landslide prone slopes in relation to logging.

Although the New Mexico logging BMPs do not specifically include the word landslide, they do state that "Road location, design, and construction shall address…the stability of slopes where roads are cut" and include topography and slope stability among the items on a planning and design checklist, which can be interpreted to include landslides and landslide-prone slopes. New Mexico defines "excessive slope" as a slope of more than 40 percent over a distance of 80 yards, requires identification of excessive slopes within cutting units, and requires a description of the ways that forest harvest practices standards will be met, as part of forest harvest plans.

Washington has a comprehensive approach to forest practices that explicitly considers landslides and their relationship to logging, based on its Forest Practices Act as implemented through rules adopted by its Forest Practices Board. The word "landslide" occurs 94 times throughout the 457-page Forest Practices Board Manual, which includes a 93-page section titled "Guidelines for Evaluation Potentially Unstable Slopes and Landforms". That section includes detailed examples of landslides, a review of office and field methods used to identify potentially unstable slopes and landforms, and advanced topics such as lidar processing and debris flow runout modeling. The document distinguishes between situations that can be adequately addressed by general practitioners and those that require extra attention from qualified experts. General practitioners can be landowners, foresters, and company engineers or consultants (including licensed geologists). A qualified expert is defined by state law as "…an engineering geologist or as a hydrogeologist (if the site warrants hydrologist expertise), with at least three years of field experience in the evaluation of relevant problems in forested lands". The state Department of Natural Resources maintains a register of experts appropriately licensed and qualified to practice geology related to forest activities. [1]

[1] Like Kentucky, Washington and 28 other states license or otherwise regulate professional geologists. Washington additionally offers specialty endorsements in engineering geology and hydrogeology that require knowledge and

Oregon likewise has a comprehensive Forest Practices Act and a guidance document for identifying designated sediment source areas likely to experience landslides that will trigger debris flows capable of delivering sediment to streams; trigger source areas within sediment source areas that are most likely to generate high-volume debris flows; and debris flow traversal areas. The guidance document, which went into effect in January 2024, prescribes a four-step office- and field-based process undertaken before commercial logging is allowed to begin, including specific geologic, geomorphologic, hydrologic, and sylvicultural criteria used to identify areas of concern. The state has developed a topographic "slopes model" to identify slopes with a high likelihood of generating landslides and/or debris flows that might impact fish-bearing streams. The slope model information, including designated sediment source and debris flow traversal areas, is available through an interactive online map service. Oregon requires that at least 50 percent of designated sediment source areas in each harvest unit be left unharvested; the unharvested areas are known as slope retention areas (SRAs). The Oregon Forest Practices Act also includes a provision for the State Forester to certify practitioners who have "…completed training and demonstrated sufficient knowledge to determine the field delineation of the final boundaries for slope retention areas." There is separate technical guidance for landslide hazard areas that have downslope public safety risks.

California annually updates a 400+ page set of forest practice rules and has a multi-stage timber harvest plan review process that includes input from the California Geological Survey. The rules define different kinds of landslides and landforms associated with landslides (e.g., headwall swales) as well as unstable areas and soils. Specifically, the rules include unconsolidated[2], non-cohesive soils and colluvium as unstable soils. The rules state, "Such soils are usually associated with a risk of shallow-seated landslides on slopes of 65% or more, having non-cohesive soils less than 5 ft. deep in an area where precipitation exceeds 4 in. in 24 hours in a 5-year recurrence interval." "Continuing landslide or soil erosion problems related to past or ongoing land-use activities" are one of the criteria that can justify classification of watersheds as sensitive to further logging in which further logging would have a potential "…to cause, or contribute to ongoing, significant adverse cumulative effect(s)". Drainage measures are to be implemented such that they avoid "…concentration of flow onto unstable or potentially unstable areas, such as known active landslides, hummocky ground, concave headwalls, or steep fillslopes." The California Geological Survey has additionally published two documents relevant to landslides and logging: Guidelines for Geologic Timber Harvesting Plans (CGS Note 45) and Factor Affecting Landslides in Forested Terrain (CGS Note 50). Table 1 includes links to both of those CGS reports.

US FOREST SERVICE SLOPE STABILITY GUIDANCE DOCUMENTS

As the result of an ambitious multi-decadal program of applied research and professional practice refinement to support science-based resource management, the U.S. Forest Service published a 3-volume slope stability reference guide for national forests (Hall et al., 1994).

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experience above and beyond those required for a basic geologist license. Oregon and California offer specialty endorsements for engineering geologists.

[2] "Unconsolidated" is used differently by geologists and geotechnical engineers. In this context, it is the geological meaning synonymous with "unlithified" or "uncemented".

Although now 30 years old and written before the existence of modern technologies like lidar and easily used GIS software to facilitate detailed spatial analyses, and not strictly a BMP document, the guide remains one of the best available references about the technical aspects of evaluating the stability of steep forested slopes in the context of resource management. It is essentially a best professional practice document for forest slope stability investigations that is readily adaptable to current technologies, for example the use of high-resolution lidar images rather than aerial photographs or topographic contour maps to identify landslide-prone slopes.

The U.S. Forest Service slope stability reference guide (Hall et al., 1994) is notable for its cross-disciplinary integration of engineering geology with geotechnical engineering and its formalization of a three-level approach to slope stability evaluation, as described here:

- Level I slope stability investigations are conducted for "…watershed analysis, ecosystem management support, and timber sale area planning" and can include office evaluation of existing geological and geotechnical information, field reconnaissance to verify preliminary office interpretations, and delineation of geomorphic zones for evaluation of the potential for slope instability from natural processes and forest management activities such as logging (Hall et al., 1994). Level I slope stability investigations can include quantitative deterministic or probabilistic slope stability analyses, as described below, to evaluate current slope stability and changes likely to occur as the result of activities such as logging.

- Level II slope stability investigations build upon the results of Level I investigations and are intended to evaluate slope stability along roads or other corridors; they include definition of road design segments based on soil and rock types, drainage, and geologic processes in each segment. Level II investigations specifically and quantitatively address changes in slope stability as a result of building roads across potentially unstable slopes.

- Level III slope stability investigations are detailed site-specific investigations used to support design of engineered stabilization measures, including preparation of field-developed engineering geologic cross-sections, sampling and measurement of relevant geotechnical properties, installation of monitoring devices such as piezometers, and advanced or design-level slope stability analysis.

QUALITATIVE AND QUANTITATIVE EVALUATION OF FOREST SLOPE STABILITY

Landslides and landforms indicative of landslide susceptibility in forested terrain are best mapped using airborne lidar-based topographic maps and their derivatives, followed by field checks to confirm interpretations made in the office.

Kentucky has had freely available statewide lidar coverage available through its KyFromAbove program (https://kyfromabove.ky.gov) since early 2017. The available products include hydro-corrected 5-ft digital elevation models (DEMs), multidirectional hillshade images, contours, and classified lidar pointclouds. Some of the initial lidar coverage, including mountainous portions of eastern Kentucky, met U.S. Geological Survey (USGS) lidar quality level QL3 rather than QL2 or above as required for inclusion in the USGS 3DEP national elevation program. Statewide coverage at quality level QL2 should be completed in 2024, allowing for production of a more resolute 2-ft statewide lidar DEM. The USGS anticipates 2025 availability of nationwide high-resolution lidar-based digital elevation model meeting its 3DEP standards (with interferometric radar coverage in Alasks).

The grid spacing, cell size, or raster size of a lidar DEM—sometimes incorrectly referred to as the DEM resolution—is important because it places limits on the size of features that can be interpreted by geologists. To illustrate the nature of resolution, Keaton and Haneberg (2013) resampled a lidar DEM depicting an obvious landslide to different raster sizes. They suggested the ability of a DEM to resolve a geologic feature such as a landslide is about 10 times its raster size. In other words, the smallest landslide that an experienced geologist might expect to resolve using a 5-ft DEM would be on the order of 50 ft by 50 ft (or 2500 ft^2). A 2-ft DEM would improve the minimum resolvable size to about 20 ft by 20 ft (or 400 ft^2). Keaton and Haneberg (2013) also discussed reasons why landslide maps, which are inherently subjective even under the best conditions, made by different geologists may differ in important respects.

Chapella et al. (2019) and Crawford et al. (2021) described a set of uniform criteria and confidence ratings used to reduce landslide mapping subjectivity on Kentucky Geological Survey projects. Crawford (2012) provided examples of visualization techniques useful for mapping landslides from lidar coverage of northern Kentucky (Figure 3). Although not focused specifically on Kentucky, Haneberg (2017) also summarized technologies and techniques useful for landslide hazard assessment. Useful techniques include combinations of multiple hillshade images with different illumination directions, multidirectional hillshade or slopeshade images, topographic contours draped over hillshade images, and use of derivative maps quantifying slope steepness, roughness, and/or curvature viewed within GIS software so that multiple map layers can be combined as necessary to support the best possible interpretation of the landscape.

Landforms indicative of landslide occurrence or susceptibility visible on lidar-derived images include concave headwalls or headscarps, convex toes or zones of accumulation, lateral scarps, and hummocky terrain. Some landslides mobilize into debris flows characterized by concave sediment source areas, levees, and depositional lobes. Not all those landforms may be visible in any specific instance, nor are all required to confidently identify landslides. Confidence ratings such as those described by Chapella et al. (2019) and Crawford et al. (2021) can be used to convey uncertainties in landslide-related feature identification. In many cases, especially for older landslides whose topographic expression may have degraded over time, indications of landslides may be subtle and require interpretation by a geologist experienced in landslide mapping. Field confirmation of office-mapped landslides is important because it can yield important additional information such as the locations of springs or seeps, vegetation changes, abnormally distorted or pistol-butted trees, and open cracks that may not be visible on lidar images or aerial photographs.

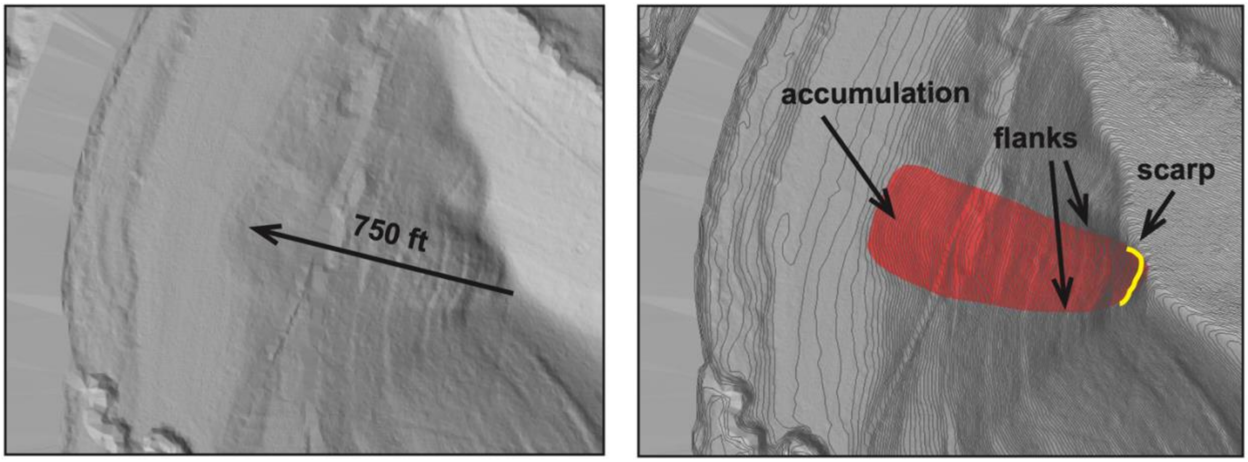

Figure 3—Example of a subtle northern Kentucky landslide identified from airborne lidar hillshade imagery and topographic contour patterns. Left: Hillshade image. Right: Hillshade superimposed with 2-ft topographic contours and annotated with landslide features. Source: Crawford (2012).

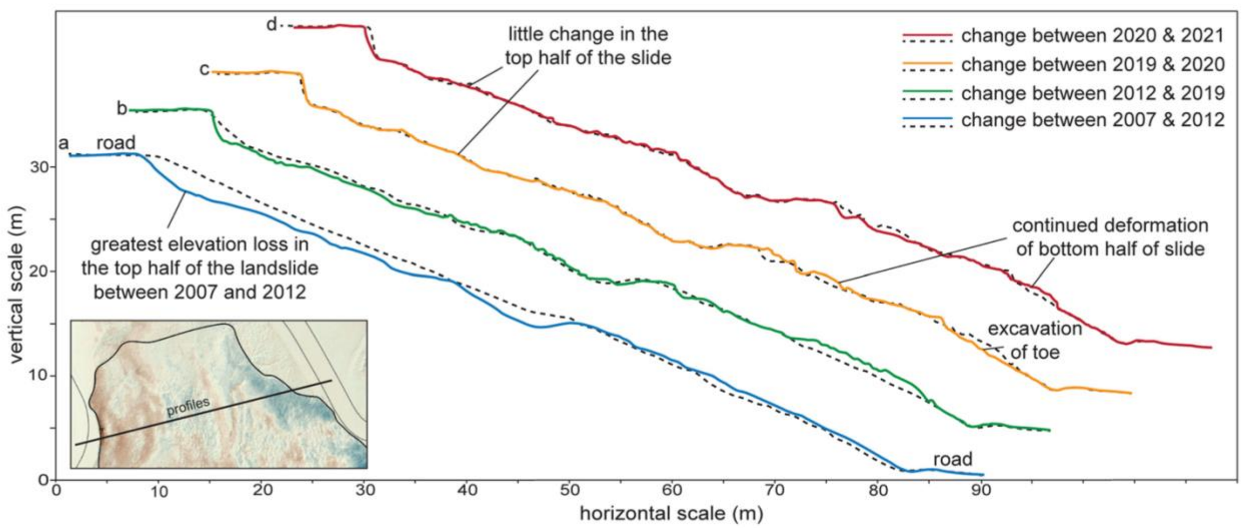

Figure 4—2007 through 2021 surface elevation changes of a northern Kentucky landslide calculated from DEMs produced from three different technologies. Inset map shows areas of elevation gain (blue) and loss (brown). Source: Johnson et al. (2023).

In situations where multiple high-resolution digital elevation datasets are available, DEM differencing may help to define areas of ongoing landslide movement. Experience has shown, however, that several steps may be necessary to account for systematic differences in DEMs produced using different technologies, with different cell sizes, and at different times. The best solution is to tie the DEMs to benchmarks surveyed immediately before or after each data collection campaign. If benchmark survey data are not available, which often occurs in cases of practical interest, comparison of elevation values in areas where is can be reasonably inferred that no change has occurred may be used as a proxy. Johnson et al. (2023) described how to correct for mismatches between DEMs produced at different times using different technologies and cell sizes and documented the decadal activity of a slow-moving landslide in northern Kentucky. Even after basic corrections are applied, DEM difference maps should always be evaluated critically with respect to the best available (typically the most recent) dataset. DEMs produced by digitizing topographic contours produced using pre-GPS analog photogrammetry, especially in steep forested terrain susceptible to landslides, can also have horizontal positional errors that require advanced rectification techniques before they can be directly compared to modern lidar DEMs (Zhu et al., 2022). In eastern Kentucky, the horizontal error between photogrammetrically derived 10-m legacy DEMs and modern lidar DEMs is in many cases 100 ft or more.

The effect of logging on slope stability can be quantitatively evaluated with the 1-D limit equilibrium slope stability equation used by the U.S. Forest Service in its watershed-level slope stability evaluation guidance document and software (Hammond et al., 1992; Hall et al., 1994; also see Haneberg, 2004 a):

$$FS = \frac{c_r + c_s + [q_t + \gamma_m D + (\gamma_{sat} - \gamma_w - \gamma_m) H_w D] \cos^2\beta \tan\phi}{[q_t + \gamma_m D + (\gamma_{sat} - \gamma_m) H_w D] \sin\beta \cos\beta}$$

where *FS* is the factor of safety against sliding; c_r and c_s are the root and soil cohesive strengths; q_t is the surcharge exerted by the weight of trees; γ_{sat}, γ_m, and γ_w are the unit weights of saturated soil below the phreatic surface, moist soil above the phreatic surface, and water; H_w is the height of the phreatic surface above a potential landslide slip surface; D is the thickness of soil above a potential landslide slip surface; β is the slope angle (in degrees); and ϕ is the effective angle of internal friction of the soil. The factor of safety, *FS*, is the ratio of resisting to driving forces acting within the slope. Values of $FS < 1$ indicate an unstable condition whereas values of $FS > 1$ indicate a stable condition. A value of exactly $FS = 1$, which is virtually never encountered in practice, represents a critical or limiting state of equilibrium within the slope. The *FS* equation can be solved in a variety of ways, from simple deterministic spreadsheet calculations computationally intensive probabilistic simulations that treat the input variables as probability distributions to account for inherent uncertainties. The U.S. Forest Service published a probabilistic computer program named LISA—for Level I Stability Analysis—that is well-documented and remains publicly available (Hammond et al., 1992). It performs calculations for a specific slope or location and is not readily applied for area-wide map-based analyses. The LISA documentation is available at:

https://forest.moscowfsl.wsu.edu/cgi-bin/engr/library/searchpub.pl?pub=1992a

and an executable MS-DOS LISA program file is available at:

https://forest.moscowfsl.wsu.edu/engr/lisa0.html

Haneberg (2004 a) developed a computationally efficient first-order, second-moment approach that allows the *FS* equation to be easily applied across entire watersheds using digital elevation model, soil geotechnical unit, and forest stand maps (Windows and Apple OS X versions of the FORTRAN computer program PISA-m, an acronym for Probabilistic Infinite Slope Analysis for Maps, are available from him upon request). Escobar-Wolf et al. (2021) subsequently developed an ArcPy implementation of the PISA-m algorithms that allows the calculations to be performed within GIS software.

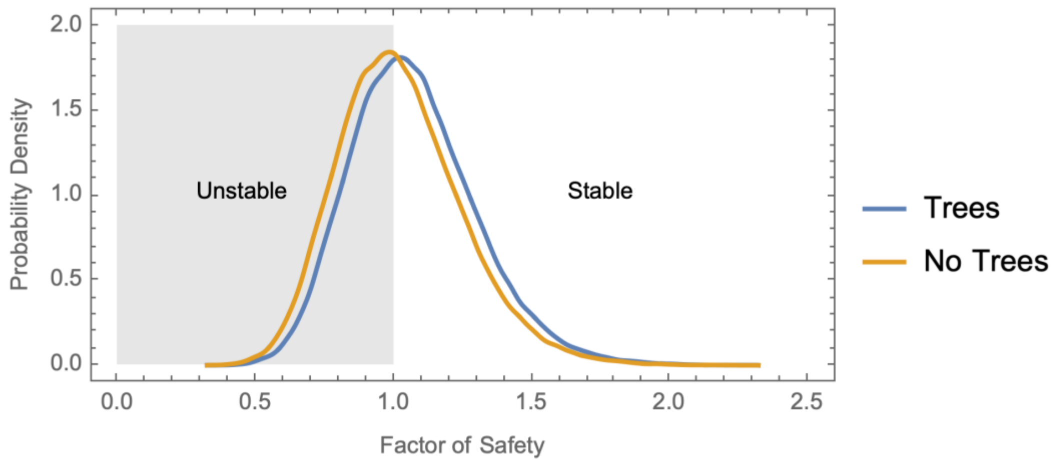

Figure 5—Results of iterative probabilistic slope stability calculations to illustrate the destabilizing effect of removing tree weight and root strength from a hypothetical slope.

As an illustration of the way the *FS* equation can be used to evaluate the effects of logging and subsequent root decay on slope stability, Figure 5 shows the results of an iterative Monte Carlo evaluation of the equation using a published sample data set from a U.S. Forest Service slope stability guidance document (Hall et al., 1994; also see Haneberg, 2004 a,b). Appendix A of this report includes the Mathematica commands used to produce the plot. For each of two scenarios—one with tree root cohesion and surcharge and the other without tree root cohesion and surcharge—the *FS* equation was solved 100,000 times with the variables for each iteration randomly selected from pre-specified probability distributions reflecting input uncertainty. Using a probabilistic formulation allows input parameter uncertainty, which is ever present and unavoidable, to be explicitly incorporated into the calculation.

In Figure 5, the blue line represents the ensemble of *FS* values calculated for the forested slope and the gold line represents the ensemble of *FS* values calculated for the unforested post-logging slope. Removing root strength and tree surcharge decreases the mean factor of safety from 1.07 to 1.02, very near the limiting state of equilibrium. The probability of sliding, Prob [$FS < 1$], for each condition is the area under its curve for values of $FS < 1$ (indicated by the gray area in Figure 5). Removal of root strength and tree surcharge from the *FS* equation in this case increases the probability of sliding from 41 percent to 50 percent. Increased pore water pressure because of logging, which is not included in the calculations, would further reduce the factor of safety and increase the probability of sliding.

The values used in this example are not intended to represent any specific or generalized Kentucky hillside; rather, they were chosen because of their previous use to illustrate the application of the method by Hall et al. (1994) and Haneberg (2004a). Use of the *FS* equation for evaluation of land management or public safety options should be overseen by appropriately licensed professional geologists and/or engineers with experience in the evaluation of steep forested slopes, particularly with regard to selection of shear strength parameters and estimation of pore water pressures likely to develop during the analysis period. Design of any remedial measures should be overseen by an appropriately licensed engineer.

Application of the logistic regression model developed by Crawford et al. (2021) to produce the Kentucky Geological Survey county-wide landslide susceptibility maps requires a level of GIS expertise impractical for application individual logging operations in Kentucky. A simplified version of the model that accounts only slope steepness, however, can be used as an approximate indicator of landslide susceptibility. If all variables except slope angle are set to zero, equation (4) in Crawford et al. (2021) becomes:

$$z = -2.0158 + 0.093\, S_{min}$$

where S_{min} is the minimum slope angle (in degrees) within an appropriately sized moving window and landslide susceptibility is given by the probability, P, as

$$P = \frac{1}{1 - e^{-z}}$$

Figure 6 is a plot of P over a realistic range of S_{min} values. Exceptionally steep slopes (above 45° or 100%) are unlikely to accumulate the soil necessary for landslides to occur, although they may be susceptible to rock falls or rock topples unlikely to deliver sediment to streams.

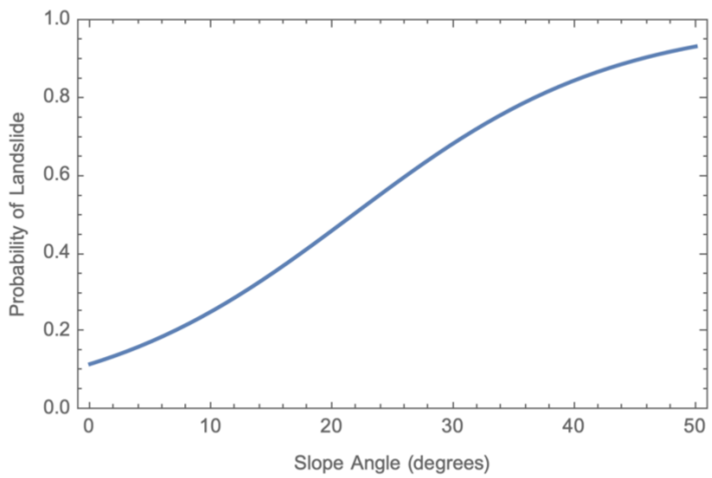

Figure 6—Plot of landslide probability as a function of minimum slope angle within a moving window alone, ignoring other geomorphological factors (cf. Crawford et al., 2021)

RECOMMENDED BEST MANAGEMENT PRACTICES

Landslides can be naturally occurring events triggered by rainfall, snowmelt, and seismic shaking. In that regard, they can be important elements of natural landscape evolution. The extensive body of literature described in this report and practical experience, however, shows that logging related activities can also increase landslide activity through loss of root strength, increases in soil moisture or pore water pressure, and roadbuilding. The BMPs described below are intended to reduce the human-driven component of landsliding in logged watersheds.

The landslide-related BMPs recommended in this section are based on a synthesis of state-of-the-practice documents from Oregon, Washington, and California (listed in Table 1) and the U.S. Forest Service slope stability reference guide (Table 1 and Hall et al., 1994), modified to account for current technology (e.g., freely available lidar digital elevation data and GIS software), regional geologic characteristics, and the current state of geologic practice in Kentucky.

Current Kentucky BMPs (Kentucky EEC, 2022) "…are designed to prevent and minimize nonpoint water pollution primarily from timber harvesting." The BMPs recommended in this section complement—not replace—existing Kentucky BMPs by providing the guidance necessary to prevent or minimize potentially significant impacts to water quality by sediment delivery from landslides.

Although these BMPs were developed in the context of eastern Kentucky topography, geology, and landslide processes, they can be adapted to other states if local factors are given proper consideration. If these recommended BMPs are adopted beyond Kentucky, it should be done in collaboration with qualified and appropriately licensed geologists and engineers to ensure that the practices are appropriate relative to regional and local geologic and geotechnical contexts. There may be justification for modifying slope angle thresholds, including or excluding locally specific geological features such as coal beds, and using different shear strength values for slope stability calculations.

The BMPs elaborated below are in a format that can be incorporated into the existing Kentucky Logging BMP Field Guide and are written at a level of specificity intended to reduce ambiguity and clarify expectations, as opposed to more general statements about avoiding landslide-prone areas.

National forests, including the Daniel Boone National Forest in Kentucky and, more broadly, in central Appalachia can incorporate the recommended BMPs (or similar regionally-tailored BMPs) into their Land and Resource Management Plans ("Forest Plans") as specific forest-wide standards through an amendment or revision process.

BMP 1: Forest landslide susceptibility and other slope stability investigations should be performed by qualified and experienced geologists and/or geotechnical engineers.

- For work on state or private lands, "qualified professional" in the context of these BMPs means a state-licensed professional geologist or civil engineer with specialized experience evaluating the geomorphology and stability of steep forested slopes.

- Employees of federal agencies such as the U.S. Forest Service are exempt from state licensing requirements but, if they do not hold active professional licenses, should otherwise be qualified through a combination of formal education, work experience, peer-reviewed publications, and/or credentials such as a Certified Professional Geologist designation from the American Institute of Professional Geologists.

- Not all states license professional geologists. If similar BMPs are adopted in a state that does not license professional geologists, qualifications should be demonstrated through a combination of formal education, work experience, peer-reviewed publications, and/or credentials such as a Certified Professional Geologist designation from the American Institute of Professional Geologists.

- Engineering design—for example, road prism, retaining structure, or slope drainage system design—should be performed under the supervision of an appropriately licensed engineer. Site investigations in support of engineering design work require collaboration of qualified geologists and engineers to ensure that data collected are both geologically representative of site conditions and provide information sufficient for design needs.

- Professionals such as foresters, hydrologists, soil scientists, biologists, or environmental scientists will generally not meet the geologist or engineer qualification, experience, and subject matter expertise expectations laid out in this BMP. If they perform the kinds of investigations outlined in these BMPs, it should be under the supervision of a qualified geologist or engineer.

BMP 2: Timber harvest planning should begin with production of a slope steepness map using the best and most current topographic data available for the watershed in which logging is anticipated.

- Unless a landowner or logging operator has collected more resolute data, the best available data for slope maps in Kentucky will generally be the most recent 2-ft DEMs from the KyFromAbove program (https://kyfromabove.ky.gov). As of April 2024, most of Kentucky is covered by airborne lidar topographic data meeting USGS quality level QL2 or better, but some areas in eastern Kentucky are currently covered only by older 5-ft lidar data that only meets QL3 requirements. The lower 48 states should have complete QL2 or better DEM coverage available in 2025 through the USGS 3DEP cooperative program (https://www.usgs.gov/3d-elevation-program).

- DEMs, especially high-resolution lidar DEMs, can sometimes benefit from gentle smoothing before derivatives like slope steepness are calculated. To preserve essential landforms, moving windows larger than 5 by 5 raster cells should be avoided if a DEM is smoothed prior to slope steepness map production. The slope steepness map and its metadata should also include a description of any kind of filtering or smoothing used (e.g., moving mean, median, or gaussian smoothing window).

- Ground surface slope angles should be calculated using a standard GIS slope function using a 3 by 3 cell moving window applied to a high-resolution lidar DEM with minimal smoothing as described it the previous bullet point.

- The slope map should clearly indicate whether the steepness is given in percent (common in agriculture and forestry) or degrees (common in geology and engineering) to avoid confusion.

- Manual estimation of slope from printed contour maps at a limited number of points or reliance on manually prepared topographic profiles is insufficient given the easy availability of high-resolution lidar DEMs.

BMP 3: For individual harvest units or road corridors in which more than 10% of the area has a ground surface slope greater than 20% (11°), a qualified professional with experience in steep forested watershed geomorphology and landslide mapping should perform an office review and site visit with a written summary report to identify areas that show evidence of past, current, or potential future landslide activity.

- The percentage of the area exceeding the 20% (11°) threshold should be calculated using all slope values within the area as described in BMP 2, either empirically from a histogram or analytically from the cumulative distribution function of a theoretical probability distribution (e.g., normal, log-normal, beta) appropriately fitted to the slope values. The written report should include slope histograms and, if used, details of the best fit probability distributions used to support the determination.

- In addition to the written report, all available data should be compiled in a GIS project using standard file formats to support the best possible interpretation and integration of information providing insights about slope stability or instability in relation to potential logging activities.

- The ensemble of information should minimally include a lidar DEM and derivatives (topographic contours, multiple hillshade and/or slopeshade images, roughness and curvature maps, and a slope map) to support multilayered geomorphological interpretation of the watershed. The written report and/or GIS metadata should include data sources and any processing or calculations done to produce each layer. Landslide susceptibility or occurrence maps and coal seam arcs available through the Kentucky Geological Survey or U.S. Geological Survey—or equivalent information available in other states—should be included as layers in the GIS project. (Information about KGS map services and GIS data availability can be found at https://kgs.uky.edu/kgsweb/main.asp)

- The compiled information should be used for office-based mapping of landforms potentially related to landsliding (e.g., concave headwalls, cove landforms, headscarps, or source areas; convex or bulked toes; lateral or internal scarps; atypically rough or hummocky topography; visibly offset roads or stream channels). It is not sufficient to simply list the coordinates of a point representing a landslide-related landform. Office mapping should be followed by field reconnaissance to verify the maps and add features such as seeps, areas of anomalous vegetation, or open cracks not visible on lidar-based layers. This is equivalent in scope and intent to a Level I slope stability analysis as described by Hall et al. (1994) as well the procedures outlined in the Oregon and Washington forest practice rule documents listed in Table 1.

- The 20% (11°) threshold is a limiting value calculated using an infinite slope factor of safety equation with a typical Appalachian sedimentary rock colluvium residual friction angle of 22°, no cohesive strength, slope parallel seepage, and a phreatic surface coincident with the ground surface. The limit is also the slope that yields 25% probability of landslide occurrence using the Crawford et al. (2021) landslide susceptibility logistic regression equation evaluated using only slope angle (all other variables set to zero), rounded to the nearest 10%. Landslides are unlikely to occur on slopes less than the threshold even if the ground is completely saturated and root strength eliminated. These values may be modified based on local experience if the BMPs are adopted in other states.

BMP 4: Within harvest units or road corridors in which more than 10% of the area has a ground surface slope greater than 20% (11°), areas susceptible or highly susceptible to landsliding should be delineated.

Portions of harvest units or road corridors should be considered **susceptible areas** if they meet one or more of the following criteria:

- Fall within an area of moderate or higher susceptibility on Kentucky Geological Survey landslide susceptibility maps (currently available only for counties in the Big Sandy Area Development District) or similar susceptibility maps in other states.

- Fall within a 100-ft buffer of a landslide polygon shown on Kentucky Geological Survey landslide occurrence maps (landslides shown on 1:24,000 geologic quadrangle maps, landslides mapped from aerial photographs, or landslides mapped from lidar) or within a 200-ft buffer of a point location in the Kentucky Geological Survey landslide database (or equivalent databases and maps that may be available in other states). The level of coverage of the maps varies across eastern Kentucky.

- Fall within a 100-ft buffer of a coal seam depicted on Kentucky Geological Survey 1:24,000 geologic quadrangle maps or in associated GIS databases. This criterion would not necessarily be applicable in areas outside of Kentucky for which relationships between coal beds and landslides do not exist.

- Fall within a 100-ft buffer of any landslide-related landform identified during office mapping and verified during field reconnaissance or initially identified during field reconnaissance.

- Have a ground surface slope between 40% and 50% (22° and 27°) based on a slope map prepared per BMP 2. These limits are based on slopes that yield 50% and 75% probability of landslide occurrence using the Crawford et al. (2021) landslide susceptibility logistic regression equation evaluated using only slope angle (all other variables set to zero), rounded to the nearest 10%.

Portions of harvest units or road corridors should be considered **highly susceptible areas** if they meet one or more of the following criteria:

- Fall within an area of high susceptibility on Kentucky Geological Survey landslide susceptibility maps (currently available only for counties in the Big Sandy Area Development District) or similar susceptibility maps in other states.

- Intersect with any landslide polygon shown on Kentucky Geological Survey landslide occurrence maps or 100-ft buffer of a point location in the Kentucky Geological Survey landslide database (or equivalent databases and maps that may be available in other states).

- Intersect with a coal seam depicted on Kentucky Geological Survey 1:24,000 geologic quadrangle maps or in associated GIS databases. This criterion would not necessarily be applicable in areas outside of Kentucky for which relationships between coal beds and landslides do not exist.

- Intersect any landslide feature identified during office mapping and verified during field reconnaissance or initially identified during field reconnaissance.

- Have an average ground surface slope greater than 50% (27°). This limit is based on slopes that yield greater than 75% probability of landslide occurrence using the Crawford et al. (2021) landslide susceptibility logistic regression equation evaluated using only slope angle (all other variables set to zero), rounded to the nearest 10%.

BMP 5: Take steps to minimize the likelihood of sediment delivery to streams—or other undesirable consequences such as road or structural damage, oil or gas pipeline rupture, or habitat loss—from landslides triggered by logging activities in susceptible or highly susceptible areas.

- Within **susceptible areas**, regeneration harvests should be avoided and at least 50% of the basal area should be left uncut OR it should be demonstrated, using quantitative slope stability analyses based on representative values for the site and reviewed by a disinterested qualified geologist or geotechnical engineer, that logging will not reduce the long-term stability of the slope below a deterministic factor of safety of $FS = 1$ or a probabilistic value of Prob $[FS < 1] = 0.50$. This will generally entail the use of a representative residual, not peak, angle of internal friction, no soil or root cohesion, and a conservatively high phreatic surface. It is recommended that the analysis assume the phreatic surface will at some time reach the ground surface during the decadal period before root strength has recovered unless other supporting data are available.

- Cutting, filling, and other earth moving for roads, landings, or other aspects of logging operations in **susceptible areas** should be subject to review and approval by a licensed engineer to ensure they will not contribute to increased instability (including design and implementation of any necessary stabilization measures).

- Logging operations in susceptible areas should be suspended during times when the ambient moisture content exceeds the plastic limit of the colluvium, residuum, or other geologic deposits on the slope.

- In **highly susceptible areas**, 100% of the area should be left uncut.

- The percentages of area left uncut should be applied to each susceptible or highly susceptible area within each harvest unit, not averaged over a group of larger areas.

- Cutting, filling, and other earth moving for roads, landings, or other aspects of logging operations should be avoided entirely in **highly susceptible areas**.

BMP 6: Implement a plan for long-term monitoring of susceptible and highly susceptible areas that intersect harvest units through the period of post-logging root strength loss and recovery, which may be on the order of a decade or more.

- A qualified geologist, geotechnical engineer, hydrologist, or soil scientist should perform at least annual field visits to inspect for signs of ongoing or incipient slope movement.

- If signs of ongoing or incipient movement are detected, consult with a qualified geologist, geotechnical engineer, hydrologist, or soil scientist to 1) determine the risk of sediment delivery to downslope streams and 2) develop a monitoring program that may include frequent field inspections, repeat surveys of monuments located to adequately characterize any slope movement, displacement gauges or transducers, piezometers and/or soil moisture sensors.

- In some cases, and depending on available resources, repeat lidar surveys (including drone-borne lidar) or interferometric synthetic aperture radar (InSAR) monitoring may be useful.

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Appendix A

Monte Carlo simulation of the Hammond et al. (1992) infinite slope stability equation

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This is a Mathematica 13 notebook with a set of commands to perform and display the results of Monte Carlo simulations of the infinite slope stability equation used in the U.S. Forest Service computer program LISA (Hammond et al., 1992). The input probability distributions are those used as an example in Hall et al. (1994) and Haneberg (2004 a) and are not intended to represent any actual slope in Kentucky. Two ensembles of results are calculated: one using the complete input dataset and a second with the tree surcharge and root cohesion values set to zero to simulate the effects of deforestation. Additional complications could be added, for example allowing the phreatic surface height and/or root strength to vary over time. Likewise, additional statistics beyond the arithmetic mean and Prob[FS < 1] could be easily added to the calculations. The primary purpose of this notebook is to demonstrate how Figure 5 in the report was produced.

In[1]:=
```
(*
First, define the function FS to calculate the Hammond et al. (1992)
 infinite slope factor of safety against sliding. Descriptions
 of the variables are in the main text of the report.
*)
```

In[2]:=
```
FS[cr_, qt_, cs_, ϕ_, γsat_, γm_, γw_, T_, Hw_, β_] :=
```

$$\frac{cr + cs + (qt + \gamma m\, T + (\gamma sat - \gamma w - \gamma m)\, Hw\, T)\, Cos[\beta]^2\, Tan[\phi]}{(qt + \gamma m\, T + (\gamma sat - \gamma m)\, Hw\, T)\, Sin[\beta]\, Cos[\beta]}$$

```
(* Set random seed to ensure reproducibility of the probabilistic results *)

SeedRandom[1234];

(* Set number of Monte Carlo iterations *)
```

```
nsteps = 100 000;

(*
Iterate the FS function nsteps times
 both with and without tree surcharge and cohesion
*)

results = Reap[
    Do[
     Module[{},
      T = RandomVariate[
        NormalDistribution[
         Mean[{1.68, 4.42}], (4.42 - 1.68) / 6
        ]
       ];
      β =  RandomVariate[
        NormalDistribution[
         Mean[{19., 33.}] , (33. - 19.) / 6
        ]
       ];
      qt =  RandomVariate[
        NormalDistribution[
         Mean[{0.72, 2.15}], (2.15 - 0.72) / 6
        ]
       ];
      cr =  RandomVariate[
        NormalDistribution[
         Mean[{0.24, 1.68}], (1.68 - 0.24) / 6
        ]
       ];
      cs =  RandomVariate[
        NormalDistribution[
         Mean[{0.24, 1.68}], (1.68 - 0.24) / 6
        ]
       ];
      ϕ =  RandomVariate[
        NormalDistribution[
         Mean[{17., 47.}] , (47. - 17.) / 6
        ]
       ];
      γm =  RandomVariate[
        NormalDistribution[
         Mean[{16.2, 21.3}], (21.3 - 16.2) / 6
        ]
```

```
      ];
     γsat = RandomVariate[
       NormalDistribution[
        Mean[{19.2, 22.0}], (22.0 - 19.2) / 6
       ]
      ];
     Hw = RandomVariate[TriangularDistribution[{0.3, 0.7}]];
     Sow[
      {FS[cr, qt, cs, ϕ Degree, γsat, γm, 9.81, T, Hw, β Degree],
       FS[0.0, 0.0, cs, ϕ Degree, γsat, γm, 9.81, T, Hw, β Degree]
      }
     ]
    ], {i, nsteps}
   ]
  ][[2, 1]];

(* Put the results into more convenient lists for clarity and plotting *)

results = Transpose[results];
resultsTrees = results[[1]];
resultsNoTrees = results[[2]];

(* Calculate mean values for each ensemble of results *)

Print["Mean FS trees = ", Mean[resultsTrees]]
Print["Mean FS no trees = ", Mean[resultsNoTrees]]

(* Calculate Prob[FS < 1] by simple counting for each ensemble of results *)

Print["Prob[FS < 1] trees = ", Length[Select[resultsTrees, # < 1 &]] / Length[resultsTrees] // N]

Print["Prob[FS < 1] no trees = ", Length[Select[resultsNoTrees, # < 1 &]] / Length[resultsNoTrees] // N]
Print["\n"]

(*
Display a plot showing smooth kernel histograms for each ensemble of results
  and a gray area showing the portions of the curves with FS < 1
 *)

Show[Graphics[{GrayLevel[0.9], Rectangle[{0, 0}, {1, 2}]}],
  PlotRange → {{-0.1, 2.6}, {-0.1, 2.1}}, Frame → True, AspectRatio → 1 / 2,
```

```
  FrameLabel → {"Factor of Safety", "Probability Density"}];

SmoothHistogram[{resultsTrees, resultsNoTrees}, Automatic, "PDF",
  Frame → True, PlotRange → {0, 2}, PlotLegends → {"Trees", "No Trees"}];

Show[%%, %,
 Epilog → {Inset[Text["Unstable"], {0.45, 1}], Inset[Text["Stable"], {1.75, 1}]}]
```

```
Mean FS trees = 1.06845

Mean FS no trees = 1.02089

Prob[FS < 1] trees = 0.40976

Prob[FS < 1] no trees = 0.49664
```

Out[16]=